

The Shapes of Galaxies and Their Halos as Traced by Stars: The Milky Way Dark Halo and The LMC Disk

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Stars and their kinematics provide one of the tools available for studies of the shapes of galaxies and their halos. In this review I focus on two specific applications: the shape of the Milky Way dark halo and the shape of the LMC disk. The former is constrained by a variety of observations, but an accurate determination of the axial ratio q_{DH} remains elusive. A very flattened Milky Way dark halo with $q_{\text{DH}} \leq 0.4$ is ruled out, and values $q_{\text{DH}} \geq 0.7$ appear most consistent with the data. Near-IR surveys have revealed that the LMC disk is not approximately circular, as long believed, but instead has an axial ratio of 0.7 in the disk plane. The elongation is perpendicular to the Magellanic Stream, indicating that it is most likely due to the tidal force of the Milky Way. Equilibrium dynamical modeling of galaxies is important for many applications. At the same time, detailed studies of tidal effects and tidal streams have the potential to improve our understanding of both the Milky Way dark halo and the structure of satellite galaxies such as the LMC.

1 Introduction

A large variety of tracers can be used to study the three-dimensional shapes of galaxies and their dark halos. Other contributions to this volume discuss the use of cold gas (e.g., HI), hot gas (X-rays), globular clusters, planetary nebulae, satellite galaxies, and gravitational lensing (both weak and strong) to study this important topic. By contrast, the present review focuses on the constraints that can be obtained from studies of stars and their kinematics. It is not possible in the context of this relatively short paper to review this topic fully for all possible classes of galaxies. So instead I focus here on two subjects for which studies of stars and their kinematics are particularly relevant: the three-dimensional shape of the Milky Way dark halo, and the intrinsic shape of the Large Magellanic Cloud.

2 The Shape of the Milky Way Dark Halo

The Milky Way consists of various separate components, including the thin disk, thick disk, central bulge, central black hole, metal-poor halo and dark halo. The general structure of the Milky Way and its various components has been reviewed by many previous authors, including, e.g., Freeman (1987), Gilmore, Wyse & Kuijken (1989), Gilmore, King & van der Kruit (1990),

Majewski (1993) and Binney & Merrifield (1998). Here I focus on the shape of the Galactic Dark Halo, a subject previously reviewed by Sackett (1998).

2.1 Constraints from Metal-Poor Halo Star Kinematics

The density distribution of the metal-poor halo has been studied using blue horizontal branch stars, RR Lyrae stars, stars counts and globular clusters. These studies have shown that the metal-poor halo is approximately a spheroidal system with an axial ratio q_{MWH} and a mass density profile that falls radially as a power-law, $\rho \propto r^{-n}$. An unweighted average of the many determinations available in the literature (as cited in, e.g., Chen et al. 2001) yields $q_{\text{MWH}} = 0.73 \pm 0.11$ and $n = 2.95 \pm 0.37$ (where the quoted errors are the RMS variations between different studies). In the solar neighborhood one can determine the three-dimensional stellar velocity ellipsoid of the metal-weak halo stars, because both line-of-sight velocities and proper motions can be measured. An unweighted average of determinations in the literature (as cited in, e.g., Martin & Morrison 1998) yields $(\sigma_R, \sigma_\phi, \sigma_z) = (155 \pm 16, 105 \pm 7, 97 \pm 7) \text{ km s}^{-1}$. One can show that these observations yield a lower limit on the axial ratio q_{DH} of the Milky Way dark halo. Hydrostatic equilibrium in an oblate collisionless system requires that there is more pressure parallel to the equatorial plane than perpendicular to it, i.e., $\mathcal{R} \equiv (\sigma_R^2 + \sigma_\phi^2)/2\sigma_z^2 > 1$. The flatter the Milky Way dark halo, the smaller the ratio \mathcal{R} for the metal-weak halo stars must be to sustain a system of axial ratio q_{MWH} . An analysis based on the Jeans equations as in van der Marel (1991) yields the strict limit that $q_{\text{DH}} > 0.4$, with all larger values allowed (depending on the unknown details of the stellar phase-space distribution function). This rules out certain models for galactic dark halos, such as those in which the dark matter all resides in the disk (e.g., Pfenniger, Combes & Martinet 1994).

2.2 Constraints from Disk Star Kinematics

Observations of the kinematics of stars in the Milky Way disk have been used to estimate that the total surface mass density of material within 1.1 kpc from the equatorial plane is $\Sigma_{\text{tot}} = 71 \pm 6 \text{ M}_\odot / \text{pc}^2$ (Kuijken & Gilmore 1991). Approximately half of this mass can be accounted for by the known luminous components of the Milky Way. From star count analyses Kuijken & Gilmore (1989) find that $\Sigma_{\text{lum}} = 35 \pm 5 \text{ M}_\odot / \text{pc}^2$, while Gould, Bahcall & Flynn find $\Sigma_{\text{lum}} = 26 \pm 4 \text{ M}_\odot / \text{pc}^2$. For any family of dark halo models that reproduce the Milky Way rotation curve, the amount of dark matter Σ_{dark} within 1.1 kpc from the equatorial plane increases as q_{DH} is decreased. Given that $\Sigma_{\text{tot}} = \Sigma_{\text{lum}} + \Sigma_{\text{dark}}$, this yields a constraint on q_{DH} (Olling & Merrifield 2000). However,

this constraint is not much more stringent than $q_{\text{DH}} = 0.7 \pm 0.3$, given the uncertainties in Σ_{lum} and the Galactic constants R_0 (the solar distance to the Galactic center) and V_0 (the circular velocity at the solar radius).

Other kinematical properties of disk stars provide the only useful constraints on the in-plane ellipticity $(b/a)_{\text{DH}}$ of the Milky Way dark halo. Evidence for non-circularity derives primarily from the local value of σ_ϕ/σ_R for thin disk stars, and from discrepancies between the Galactic rotation curve at $R > R_0$ when estimated using stellar and gaseous tracers respectively. Kuijken & Tremaine (1994) conclude tentatively from this evidence that the gravitational potential has an ellipticity of ~ 0.08 , with the sun positioned roughly along the minor axis. The gravitational potential of a mass distribution is always rounder than the density distribution, and the in-plane ellipticity of the dark halo density must therefore be $(b/a)_{\text{DH}} \approx 0.2$. This would be somewhat surprising, given that studies of other disk galaxies have found that their ellipticities do not typically exceed ~ 0.1 (Franx & de Zeeuw 1992; Rix & Zaritsky 1995; Schoenmakers, Franx & de Zeeuw 1997).

2.3 Constraints from Tidal Streams of Stars in the Halo

When an infalling satellite is tidally disrupted by a galaxy, the tidally stripped material will phase-mix along the satellite orbit. This gives rise to tidal streamers (Johnston, Hernquist & Bolte 1996). It has been suggested that much of the metal-weak halo was built up in this way (Searle & Zinn 1978), and evidence for this is now accumulating (Helmi et al. 1999). In a circular potential the tidal stream will move in a planar orbit, and will appear to an observer approximately as a great circle on the sky. By contrast, in an axisymmetric potential the orbit will precess, and the projected distribution on the sky will be considerably more spread out. Using a study of carbon stars, Ibata et al. (2001) recently found a stream that is associated with the Sagittarius dwarf galaxy. They argue that the stream has only a small width on the sky, and from numerical simulations it is inferred that this implies $q_{\text{DH}} > 0.7$ for the Milky Way dark halo. However, the stream has so far been delineated by only 38 carbon stars. So while this is a promising new method for studying the Milky Way dark halo shape, the resulting constraint on q_{DH} should be considered somewhat tentative at present, given the limited statistics.

2.4 Constraints from Other Tracers

Although this review focuses on stars and their kinematics, it is useful in the present context to discuss what other tracers and methods can be used to constrain the shape of the Milky Way dark halo.

[HI flaring] The thickness of the HI layer of the Milky Way increases with galactocentric distance. The exact amount of disk flaring is directly related to the axial ratio of the dark halo through the equations of vertical hydrostatic equilibrium, as modeled in detail by Olling & Merrifield (2000). Unfortunately, the results of this analysis depend sensitively on the poorly known Galactic constants R_0 and V_0 . When acceptable margins on these constants are taken into account, the observed HI flaring can be fit with models in which q_{DH} is anywhere between 0.5 and prolate values > 1 . This degeneracy can be lessened when the models are required to also fit the constraints from the stellar kinematics of the thin disk, as described in Section 2.2 (because the latter have a different functional dependence on the Galactic constants). Olling & Merrifield (2000) advocate $q_{\text{DH}} \sim 0.8$ as their best-fit value, but this is obtained for values $R_0 \approx 7.6 \text{ kpc}$ and $V_0 \approx 190 \text{ km s}^{-1}$ that differ considerably from the commonly accepted values. In the absence of accurate independent determinations of R_0 and V_0 these results therefore remain tentative.

[Microlensing] In a dark halo composed of massive compact halo objects (MACHOs) the optical depth for microlensing in different directions will depend on the axial ratio q_{DH} of the dark halo. Sackett & Gould (1993) argued that the ratio of the optical depths towards the LMC and the SMC can thus be used to estimate q_{DH} . Although surveys towards the LMC and the SMC have indeed detected microlensing, the prospects for a determination of q_{DH} are not promising. The latest results from the MACHO collaboration indicate that only $\sim 20\%$ of the dark halo is composed of MACHOs (Alcock et al. 2000). Hence, microlensing can only yield constraints on q_{DH} if the MACHOs trace the rest of dark halo material, and this is unclear as long as the nature of the MACHOs remains unknown. In addition, there remains controversy concerning the contribution of LMC and SMC self-lensing to the observed optical depths (e.g., Sahu 1994; Afonso et al. 2000), which complicates any interpretation of the data.

3 The Intrinsic Shape of the LMC

The LMC is our nearest significant neighbor galaxy. While for the Milky Way the shape of the dark halo continues to be one of the outstanding questions, for the LMC it is still an important question what the shape of the stellar component itself is. This is of fundamental importance for several issues, including the study of the Milky Way dark halo through modeling of the Magellanic

Stream and the tidal disruption of the Magellanic Clouds (e.g., Moore & Davis 1994; Lin, Jones & Klemola 1995; Gardiner & Noguchi 1996) and the study of compact objects in the dark halo through microlensing studies (e.g., Sahu 1994; Alcock et al. 2000).

3.1 The Vertical Structure of the LMC

The LMC is believed to be approximately planar. This is supported by: (a) the small vertical scale height (< 0.5 kpc) indicated by the line-of-sight velocity dispersion of Long Period Variables (Bessell, Freeman & Wood 1986), star clusters (Freeman, Illingworth & Oemler 1983; Schommer et al. 1992), planetary nebulae (Meatheringham et al. 1988) and carbon-rich AGB stars (Alves & Nelson 2000); and (b) the relatively small scatter in the period-luminosity-color relationships for Cepheids (Caldwell & Coulson 1986) and Miras (Feast et al. 1989). There is some evidence for an increasing scale height at large radii (Alves & Nelson 2000). There is no evidence for a halo component in the LMC comparable to that of our own Galaxy (Freeman et al. 1983), although it has been a topic of debate whether the LMC contains secondary populations that do not reside in the main disk plane (e.g., Luks & Rohlfs 1992; Zaritsky & Lin 1997; Zaritsky et al. 1999; Weinberg & Nikolaev 2000; Zhao & Evans 2000).

3.2 The Viewing Angles of the LMC Disk Plane

It has only very recently been possible to accurately determine the viewing angles of the LMC disk plane: the inclination angle i and the line-of-nodes position angle Θ . The method relies on the fact that one side of the LMC disk plane is closer to us than the other, which causes stars on one side of the LMC to be brighter than those on the opposite side. Van der Marel & Cioni (2001) detected this effect using an analysis of spatial variations in the apparent magnitude of features in the color-magnitude diagrams extracted from the near-IR surveys DENIS (e.g., Cioni et al. 2000a) and 2MASS (e.g., Nikolaev & Weinberg 2000). Sinusoidal brightness variations with a peak-to-peak amplitude of ~ 0.25 mag were detected as function of position angle. The same variations are detected for asymptotic giant branch (AGB) stars (using the mode of their luminosity function) and for red giant branch (RGB) stars (using the tip of their luminosity function), and these variations are seen consistently in all of the near-IR DENIS and 2MASS photometric bands. The best fitting geometric model of an inclined plane yields an inclination angle $i = 34.7^\circ \pm 6.2^\circ$ and line-of-nodes position angle $\Theta = 122.5^\circ \pm 8.3^\circ$.

3.3 *The Shape of the LMC Disk*

The LMC morphology has been studied with many different tracers (reviewed by Westerlund 1997), including e.g. stellar clusters, HII regions, supergiants, planetary nebulae, HI emission and non-thermal radio emission. However, near-IR surveys provide the most accurate view because of the large statistics and insensitivity to dust absorption. van der Marel (2001) used the 2MASS and DENIS data to construct a star count map of RGB and AGB stars. The resulting LMC image shows the well-known bar, but indicates that the intermediate-age/old stellar component is otherwise quite smooth (see also Nikolaev & Weinberg 2000, Cioni et al. 2000b). This contrasts with the younger populations that dominate the light in optical images. Ellipse fitting shows that the position angle and ellipticity profile have large radial variations at small radii, but converge to $\text{PA}_{\text{maj}} = 189.3^\circ \pm 1.4^\circ$ and $\epsilon = 0.199 \pm 0.008$ for $r > 5^\circ$.

Van der Marel (2001) stressed the importance of the fact that Θ differs from PA_{maj} . This indicates that the LMC disk is not circular. Deprojection of the near-IR starcount map yields an intrinsic ellipticity 0.31 in the outer parts of the LMC. This elongation had not been previously recognized, because traditionally the line of nodes position angle Θ had generally been determined under the (incorrect) assumption that the LMC is circular (as discussed and reviewed in van der Marel & Cioni 2001).

3.4 *The Tidal Effect of the Milky Way*

The elongation of the LMC is considerably larger than typical for disk galaxies (see the discussion in Section 2.2). Weinberg (2000) recently stressed the importance of the Galactic tidal field for the structure of the LMC. To lowest order one would expect the main body of the LMC to become elongated in the direction of the tidal force, i.e., towards the Galactic Center. By contrast, material that is tidally stripped will phase mix along the orbit (see Section 2.3). For an orbit that is not too far from being circular, one thus expects the elongation of the main body to be perpendicular to any tidal streams that emanate from it (a generic feature of satellite disruption that is often seen in numerical simulations and observations, e.g., Johnston 1998; Odenkirchen et al. 2001). The results of van der Marel (2001) show indeed that LMC is elongated in the general direction of the Galactic center, and is elongated perpendicular to the Magellanic Stream and the velocity vector of the LMC center of mass. This suggests that the elongation of the LMC has been induced by the tidal force of the Milky Way.

4 Conclusions

Stars and their kinematics provide an important tool for the study of the shapes of galaxies and their dark halos. The discussions in this review show that while for the nearest galaxies some important lessons have been learned, other issues continue to be poorly understood. The Milky Way dark halo cannot be very flattened, but otherwise its axial ratio is not well constrained. For the LMC we have only recently learned that its disk is quite elongated, and that the tidal effect of the Milky Way on LMC structure may be larger than previously believed. It appears that detailed studies of tidal effects and tidal streams have the potential to improve our understanding of both the Milky Way dark halo and the structure of satellite galaxies such as the LMC.

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